

REVIEW

Blood Supply to the Human Spinal Cord. I. Anatomy and Hemodynamics

ANAND N. BOSMIA¹, ELIZABETH HOGAN¹, MARIOS LOUKAS², R. SHANE TUBBS¹, AND AARON A. COHEN-GADOL^{3*}

¹*Pediatric Neurosurgery, Children's Hospital of Alabama, Birmingham, Alabama*

²*Department of Anatomic Sciences, St. George's University School of Medicine, St. George's, Grenada*

³*Goodman Campbell Brain and Spine, Department of Neurological Surgery, Indiana University School of Medicine, Indianapolis, Indiana*

The arterial network that supplies the human spinal cord, which was once thought to be similar to that of the brain, is in fact much different and more extensive. In this article, the authors attempt to provide a comprehensive review of the literature regarding the anatomy and known hemodynamics of the blood supply to the human spinal cord. Additionally, as the medical literature often fails to provide accurate terminology for the arteries that supply the cord, the authors attempt to categorize and clarify this nomenclature. A complete understanding of the morphology of the arterial blood supply to the human spinal cord is important to anatomists and clinicians alike. Clin. Anat. 00:000–000, 2013. © 2013 Wiley Periodicals, Inc.

Key words: spinal cord; vascular supply; anatomy; nervous system

INTRODUCTION

Gillilan (1958) stated that Adamkiewicz carried out and published in 1881 and 1882 the first extensive study on the blood vessels of the spinal cord, and that his work and a study of 29 human spinal cords by Kadyi (1889) were the only sources of accurate, detailed information and basic terminology on this subject up until the late 1930s. An important caveat for this article concerns the terminology employed to refer to specific components of the spinal cord's vascular anatomy since sources in the literature have used different terms to refer to the same anatomical structures.

It has been suggested that the unbranched arteries that join the anterior spinal artery or the posterior spinal arteries be called "segmental medullary arteries" to distinguish them from the radicular arteries that supply the nerve roots (Figs. 1 and 2). Alternative terms used to refer to such arteries that feed into the anterior or posterior spinal arteries are "medullary artery" and "radicular feeder." Separate studies have used different terms to distinguish these arteries from radicular arteries, which do not feed into the anterior or posterior spinal arteries. The terms "radiculomedullary arteries" and "radiculopal arteries" refer to anterior radicular

(segmental medullary) arteries and posterior radicular (segmental medullary) arteries, respectively (Thron, 1988). The smaller radicular arteries branch from the spinal branch of the segmental artery (branch) of parent arteries such as the vertebral arteries, ascending and deep cervical arteries, etc. However, the term "radicular artery" can refer to both the segmental medullary artery and the small radicular branches, which feed only the nerve roots (Martirosyan et al., 2011).

EMBRYOLOGY

There is no difference in pattern, relative size, or relationship between the spinal arteries of infants and

*Correspondence to: Aaron A. Cohen-Gadol, MD, MSc, Goodman Campbell Brain and Spine, Department of Neurological Surgery, Indiana University School of Medicine, 355 W. 16th Street, Suite 5100, Indianapolis, IN 46202, USA. E-mail: acohenmd@gmail.com

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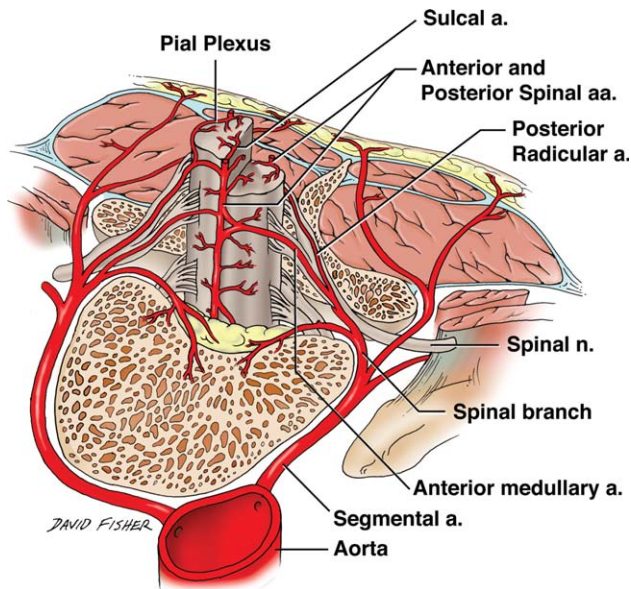


Fig. 1. Schematic view of the blood supply of the spinal cord stemming from the aorta. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

adults. The vascular system is fully laid down well before 6 months of age, and there are no significant changes thereafter in the spinal cord (Gillilan, 1958). In the first few weeks of development, 31 somites are formed. From the rostral to the caudal end of the embryo, each of these receives one pair of arteries arising from the dorsal aorta, the segmental arteries. These branches course dorsally to supply two groups of territories: (1) bone and muscle derivatives and (2) neural derivatives (Lasjaunias and Berenstein, 1990).

Development of the neural plate starts during the third gestational week and is derived from the embryologic ectoderm. This process is induced by the underlying notochord and adjacent mesoderm, which regulates the development of the surrounding structures, including the nerves, blood vessels, and somites. In this stage, the angioblasts initially form small cell clusters, or blood islands, within the embryonic and extraembryonic mesoderm. Formation of the neural tube begins early in the fourth week (days 22–23) with closure of the rostral and caudal neuropore during days 25–27, which coincides with the establishment of the intrinsic vascular circulation within the spinal cord; intrinsic development of spinal cord vascularization starts in the first month of embryonic life when sulcal arteries appear on the dorsal aspect of the paired ventral axis. They remain lateralized even after fusion of the anterior spinal axis. The pial network, superficial to the cord, and the dorsal longitudinal systems develop secondarily (Lasjaunias and Berenstein, 1990; Krings and Geibprasert, 2009). Around the neural tube, a network of capillaries will later give rise to dominant paths, which rapidly individualize into longitudinal arterial axes (Lasjaunias and Berenstein, 1990). Two longitudinal collection

systems form in the subarachnoid space at the dorsal and ventral surface of the cord, later joining the epidural space laterally through numerous radicular veins. These veins do not necessarily follow the spinal nerves as the arteries do. This adult-type venous drainage pattern is seen by the tenth gestational week (Krings and Geibprasert, 2009). From the sixth week to the fourth month of uterine life, the definitive adult pattern will progressively be formed. This development occurs in a cranio-caudal direction (Lasjaunias and Berenstein, 1990).

The two ventral arterial channels of the neural tube migrate medially and eventually fuse over most of their length to become a single ventral longitudinal neural axis, the anterior spinal axis. Dorsal to the neural tube, the pial network separates into two paramedian dominant streams, whose appearance long remains tortuous and ill-defined, before becoming the two posterior spinal arteries (Lasjaunias and Berenstein, 1990).

Summation and desegmentation lead to regression of the anterior and posterior radicular sources of supply to the ventral axis and pial network. Four to eight anterior radicular arteries remain; the others regress almost completely. The remnants of these segmental branches to the neural derivatives take over the supply to the nerves, bone, and dura. This regression is prominent in the caudal region, where a single anterior radicular artery persists in most instances. The obliquity of the nerves and the course of the arteries can be recognized, testifying to the growth differences between the spine and spinal cord. The terminal stages after the fourth month of embryonic life show an increasing obliquity of the nerve roots and tortuosity of the longitudinal arterial axis until the eighth and ninth months. This tortuous aspect of the arteries tends to stabilize, but can still be observed in full-term fetuses. The extraspinal arteries undergo few changes or none at all. The intercostal and lumbar arteries preserve the same aspect. In the cervical region, persistent intersegmental anastomoses will create the deep cervical arteries, vertebral arteries, and ascending cervical arteries.

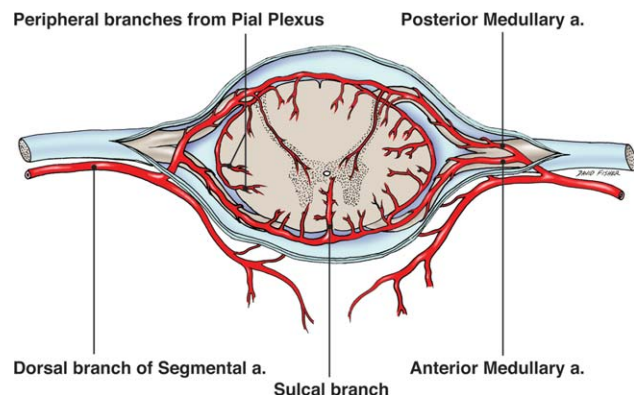


Fig. 2. Axial view of the blood supply to the spinal cord and rootlets. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

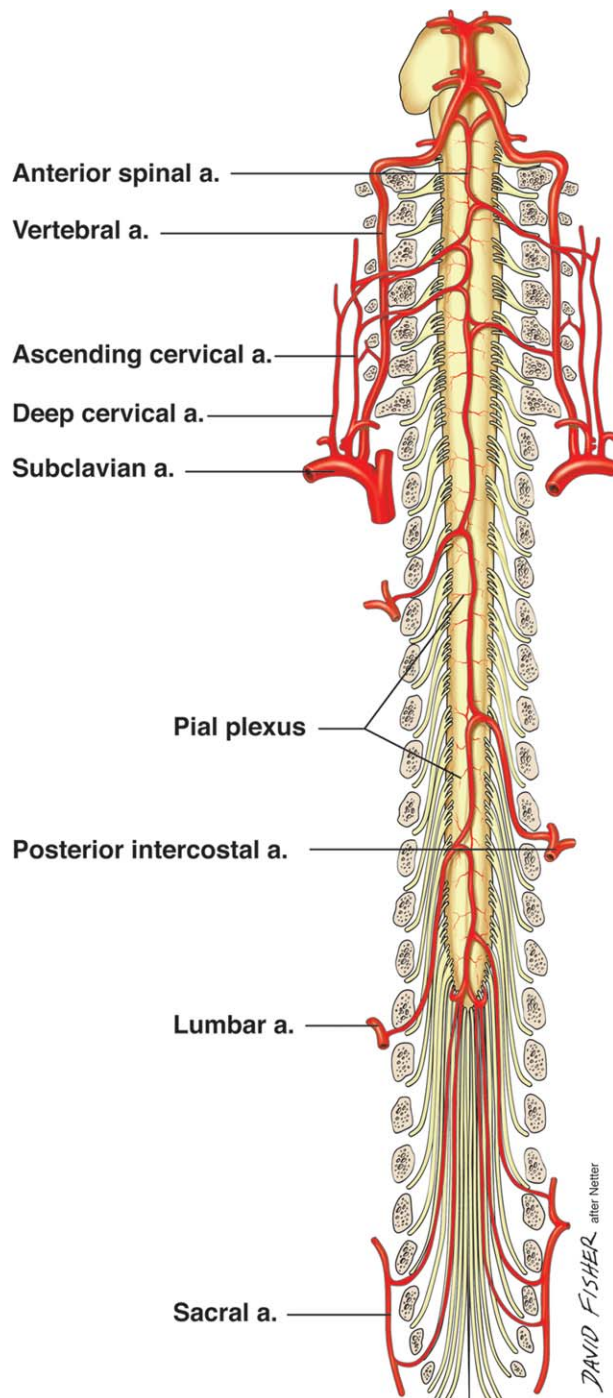


Fig. 3. Longitudinal schematic of the blood supply to the spinal cord from regional sources. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In the sacral area, vascular rearrangement involving the umbilical and lumbar arteries modifies the pre-transverse and longitudinal pattern seen at the cranial levels. The lateral sacral arteries, which are homologues of the ascending cervical vessels, will be taken

up laterally by the developing iliac arteries, whereas the dorsal aorta regresses to become the middle sacral artery. Similarly, the supreme intercostal and some large costocervical arteries represent the same longitudinal ventral extraspinal variants (MacNalty and Horsley, 1909).

EXTRASPINAL ARTERIES

Extraspinal arteries are the major afferent vessels that feed the spinal arterial network, and account for the pathway of blood from the aorta (El-Toraei and Juler, 1979; Kawaharada et al., 2004). These arteries are fully developed segmental arteries from 6 months of fetal age onward, contribute to the anterior spinal artery, and are 2–17 in number (Gillilan, 1958). Since the blood supply to any area of the spinal cord is proportional to the cross-sectional area of its gray matter, it is not necessarily the number of vessels that perfuse the area which will contribute to the blood supply, but also the collateral circulation that is present (Crosby and Gillilan, 1962).

The segmental arteries that supply the spinal ganglia and the spinal cord arise from: the vertebral arteries, the ascending cervical arteries, and the deep cervical arteries in the cervical region; the intercostal arteries in the thoracic region; the lumbar arteries, the iliolumbar arteries, and the lowest lumbar artery in the lumbar region; and the lateral sacral arteries in the sacral and coccygeal regions of the spinal cord (Fig. 3; Yoss, 1950).

The dorsal division of a segmental artery gives off branches to the corresponding vertebra and one spinal branch, which enters the intervertebral foramen and is often united with the branch supplying the vertebra. After having given off the spinal branch, the remainder of the dorsal division of the segmental artery follows the dorsal division of the spinal nerve and supplies the paramedian region of the back. This holds true for the intercostal arteries, lumbar arteries, iliolumbar arteries, and the lateral sacral arteries (Bergmann and Alexander, 1941).

The cervicothoracic region of the spinal cord is fed mainly by the vertebral arteries that combine intracranially, and from which arise the anterior and posterior spinal arteries, as well as a radicular artery at ~C3 (Fig. 4; El-Toraei and Juler, 1979; Novy et al., 2006). In the cervical region of the spinal cord, the upper three to five cervical spinal arteries are derived from the segmental branches of the vertebral arteries, whereas the lower cervical spinal arteries are derived from the segmental branches of the ascending and deep cervical arteries and the supreme intercostal artery. However, any neck vessel in the vicinity may give rise to the cervical segmental arteries. With regard to the embryologic development of these vessels, the cervical cord is supplied entirely by arteries arising from the seventh dorsal segmental artery. However, which arteries finally become the permanent feeding channels is variable (Gillilan, 1958). Some lower cervical segmental branches occasionally arise directly from the subclavian artery (Crosby and Gillilan, 1962).

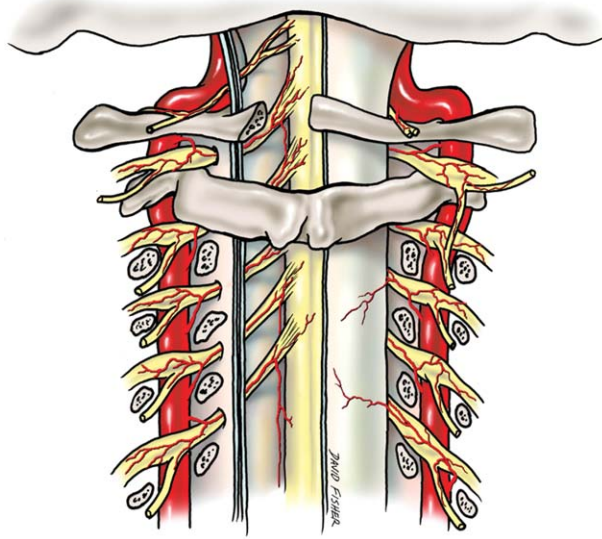


Fig. 4. Posterior view of the craniocervical region noting the radicular branches of the vertebral artery traveling medially to supply roots and spinal cord. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In the cervical region, the spinal branches of the ascending cervical artery enter the intervertebral foramina after union with the spinal branches from the vertebral artery and the deep cervical artery. Thus, the vertebral artery, for the first to the sixth cervical vertebrae, and the deep cervical artery, for the lower cervical segments, are supplemented by the spinal branches of the ascending cervical artery. However, the same arrangement of arteries is not seen near the spinal ganglia in the lower (e.g., thoracic) segments, for in these segments the branches of the ascending cervical artery anastomose with the vertebral and the deep cervical arteries before they give off their spinal branches (Bergmann and Alexander, 1941).

In the cervical region, the arterial blood will reach the spinal cord via 8–10 unpaired anterior medullary arteries that branch off the posterior segmental arteries in the head and neck (Crosby and Gillilan, 1962). There will be at least one medullary artery (it may be paired) at the cervical enlargement at C6 and one to three other arteries above and below this artery, whereas it is usually absent from C8 (Dunning and Wolff, 1937). These anterior medullary arteries will not branch, but will anastomose directly with the anterior spinal artery. They do not supply the nerve roots; therefore, they should not be called “radicular arteries” (Dunning and Wolff, 1937). The segmental branches of the various arteries supplying the spinal cord give rise to either radicular or medullary branches. Usually, at least two anterior medullary arteries of large size join the anterior spinal artery in the cervical region. The larger of these is located at the cervical enlargement, at either the fifth or sixth cervical segment, but rarely it may be at the fourth or

seventh cervical segment (Gillilan, 1958). The artery of the cervical enlargement usually stems from the deep cervical artery at the level of C6; at C8, a division of the costocervical artery provides a radicular feeder, and occasionally another radicular artery branches from the ascending cervical artery (Infante and Alter, 1970; Lazorthes et al., 1971). The second largest vessel occurs most often at the third cervical segment, but can occur also at the second or fourth cervical segment (Gillilan, 1958).

The descending aorta gives off nine intercostal pairs and a subcostal pair of regularly placed posterior segmental arteries. Following in the series are four lumbar arteries arising from the aorta opposite the four upper lumbar vertebrae, and an iliolumbar (or fifth lumbar) artery from either the aorta or the middle sacral artery. The spinal branches of the posterior segmental arteries enter the corresponding intervertebral foramina (Gillilan, 1958).

All spinal nerve roots have associated radicular or segmental medullary arteries and most have radicular arteries. Both types of arteries run along roots, but radicular arteries end before reaching the anterior or posterior spinal arteries; in contrast, larger segmental medullary arteries continue on to supply a segment of the anterior or posterior spinal arteries. Kadyi (1889) noted this distinction as well. He showed that the anterior spinal artery was reinforced in its course by several spinal branches that passed to the cord along the anterior or posterior roots. Most of the spinal branches found entering along the course of many of the anterior spinal roots were very small, and presumed to be supplying blood to the root only. However, a few of the spinal branches were larger and appeared to carry blood to the anterior spinal artery. Such branches were most common at the level of the fifth or sixth cervical segment and in the lower

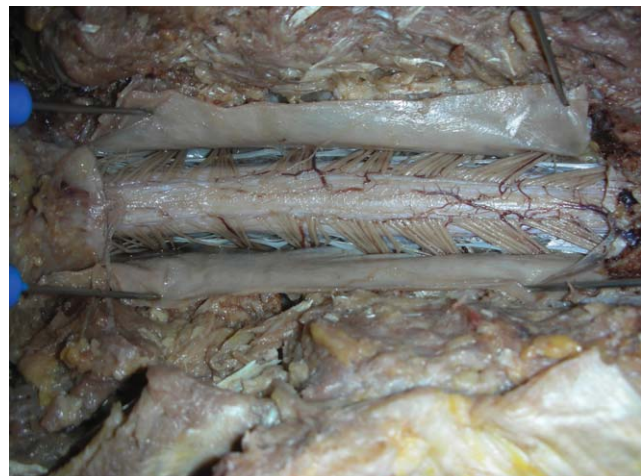


Fig. 5. Exposed dorsal surface of the thoracolumbar portion of the spinal cord in a cadaver. Note the lack of arteries in the thoracic (left) versus lumbar (right) regions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

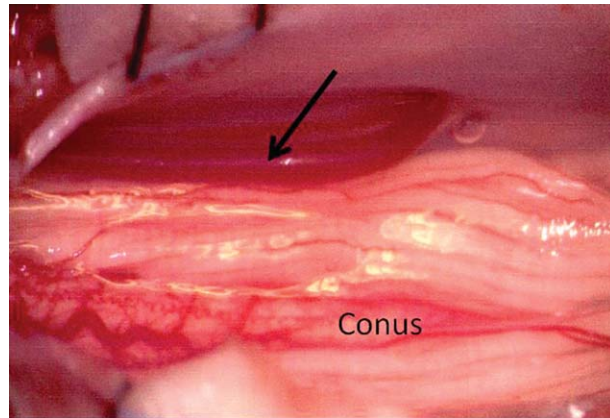


Fig. 6. Intraoperative photograph noting a large right-sided artery of Adamkiewicz (arrow). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

thoracic or upper lumbar level and were usually unpaired (Bolton, 1939).

In the thoracic and lumbar regions, the posterior segmental arteries that supply the spinal cord will arise in pairs from the thoracic (Fig. 5) and lumbar aorta, respectively, as well as from the common iliac arteries and the lateral sacral or associated arteries near the sacral foramina (Crosby and Gillilian, 1962). The thoracic region will have 2–4 small medullary arteries that will branch from the posterior segmental arteries and join the anterior spinal artery (Crosby and Gillilian, 1962).

The midthoracic region of the spinal cord has poor vascularity and is relatively tenuous compared with the other regions (Fig. 5), and is most often fed by a single artery, which branches from the intercostals at the level of T7. Additionally, the anastomotic network of the thoracic region is not as intricate as the lumbar and cervical levels. Occasionally, the anterior spinal artery may become discontinuous at the midthoracic region, contributing to its vulnerability to compromise from hypoperfusion or occlusion of a single artery (Bradley et al., 2004).

Although not to the extent of the cervicothoracic region, the thoracolumbar region has a rich vascular supply, which comes commonly from a single vessel called the artery of the lumbar enlargement, or artery of Adamkiewicz (Fig. 6; Turnbull et al., 1966; Tveten, 1976; Alleyne et al., 1998). The artery of Adamkiewicz is the largest of the medullary arteries and has some degree of variability in its location (Uotani, 2008). This artery has been measured at 872 microns in the adult and 748 microns in the newborn (Suh and Alexander, 1939). The artery of Adamkiewicz typically arises between the levels of T9 and T12 in 75% of the population, between T5 and T8 in 15%, and between L1 and L2 in 10% (Suh and Alexander, 1939). This artery takes a long course upward at an oblique angle and accompanies the anterior nerve root with which it is associated. However, when it meets the anterior spinal artery, it takes an acute turn caudally and thereby directs most of its blood flow downward

(Crosby and Gillilian, 1962). Often, when the artery of Adamkiewicz arises from higher levels, between T5 and T8, it is supplemented by an additional conal artery, which emanates from the internal iliac artery; this conal artery is referred to as the Desproges-Gotteron artery (Novy et al., 2006). This artery is usually located between L2 and L5 (Novy et al., 2006). Its most frequent site is the second lumbar segment, but it may be observed at any segment between the eighth thoracic and the fourth lumbar segments of the spinal cord (Suh and Alexander, 1939).

A study of acute spinal cord lesions in monkeys induced by occlusion of the anterior medullary arteries by Yoss (1950) showed that pathologic results correlated directly with the size of the blood vessels involved. Occlusion of the artery of Adamkiewicz results in severe damage to the anterolateral two-thirds of the spinal cord at the level of entrance of this artery into the spinal cord and for a distance above and below. Interference with the blood supply to the roots apparently does not produce acute lesions. Yoss noted that the clinical picture following injury to the cauda equina is similar to that seen after occlusion of the artery of Adamkiewicz (Gillilian, 1958).

The arteries supplying the sacral nerves and roots may come from the lateral sacral arteries, which are branches of the internal iliac arteries, or, less frequently, from the middle sacral artery. The lateral sacral artery gives off a superior branch to the first anterior sacral foramen. Its inferior branch sends spinal rami to the second, third, and fourth anterior sacral foramina. There is extensive anastomosis between these arteries on the anterior surface of the sacrum (Gillilian, 1958).

With the inadequacy of the spinal arterial system to furnish collateral circulation within the cord itself, the extraspinal arterial channels assume great importance. These are both limited in number and variable in their levels of entrance. Any condition that interferes with the flow of blood over one or more of the segmental arteries contributing to the anterior spinal artery produces a lesion similar to that caused by occlusion of the anterior spinal artery (Gillilian, 1958).

RADICULAR ARTERIES

As stated earlier, the dorsal division of a segmental artery provides branches to the corresponding vertebra and one spinal branch (Bergmann and Alexander, 1941). At the intervertebral foramen, the spinal branch can divide into an anterior radicular branch and a posterior radicular branch. These radicular branches, or radicular arteries, supply their corresponding nerve roots and disappear within these structures. Near its origin, the posterior radicular artery gives off a ganglionic branch (Becske and Nelson, 2009).

If involved in the vascularization of the spinal cord proper, radicular arteries are classified as radiculomedullary (when they supply the anterior spinal artery) or radiculopial (if they contribute to the posterior spinal artery and surface vasocorona of the spinal cord; Becske and Nelson, 2009). Bergmann and Alexander

(1941) observed that these spinal branches, after supplying the posterior root ganglia, send mainly insignificant arteries to the anterior and posterior nerve roots. Such small arteries terminate either on the roots or immediately after reaching the spinal cord (Yoss, 1950). These are the radicular branches, or radicular arteries. Usually six to eight of the anterior branches from the spinal artery are of significant size and travel on the anterior roots to the spinal cord where they contribute to the anterior spinal artery. Likewise, ~8–16 significant posterior branches travel on the posterior nerve roots and supply the two posterior spinal arteries (Yoss, 1950). Both groups of branches are referred to as segmental medullary arteries. The posterior medullary arteries are smaller, in general, than the anterior medullary arteries (Crosby and Gillilian, 1962). Although the anterior vessels are wider in luminal diameter, the posterior vessels are more numerous (Turnbull et al., 1966).

The segmental medullary arteries compose the portion of the arterial network that not only supplies blood to the cord, but also connects extraspinal vessels to the main spinal arteries (Crosby and Gillilian, 1962). These vessels show a high degree of variability in number and luminal size, so much so that some vessels will serve as major suppliers of blood flow to the spinal arterial system, whereas others may only perfuse a few neurons that they contact directly (Turnbull et al., 1966). During embryologic development, 62 such arteries (31 pairs) are formed to supply the cord, but most of these vessels will degenerate with development (Thron, 1988). On average, only seven or eight vessels contribute toward perfusion of the spinal cord (Sahs, 1942). These vessels enter the vertebral canal along with the spinal nerve roots, after which they bifurcate into anterior and posterior radicular branches and continue to follow their respective root (Rodriguez-Baeza et al., 1991; Alleyne et al., 1998; Novy et al., 2006; Nijenhuis and Backes, 2009).

Radiculomedullary arteries arise from the segmental branches of the vertebral, ascending and deep cervical, thoracic, and lumbar arteries. The origin and number of radiculomedullary arteries range from six to ten in adults and include the artery of the lumbar enlargement (artery of Adamkiewicz) and the artery of the cervical enlargement. On angiography, radiculomedullary arteries, which contribute to the anterior spinal artery, show a "hairpin" appearance and midline location. Ten to twenty-eight radiculopial arteries contribute to the posterior spinal arteries. They also form acute hairpin bifurcations, but are distinguished from the anterior spinal artery by their typical off-midline location (Lasjaunias and Berenstein, 1990).

The range in caliber of the larger, medullary vessels extends from 340 to 1,122 μm . The range in caliber of the smaller, radicular vessels extends from 34 to 214 μm ; again, these vessels do not contribute significantly to the intraspinal circulation. Most of them exhaust themselves about the roots (Suh and Alexander, 1939).

The number of radicular feeders varies by region of the spinal cord (Tveten, 1976). A study by Tveten

(1976) showed the number of anterior medullary arteries in the cervicothoracic region has a range of 1–6 arteries with an average of three arteries, the midthoracic region a range of one to five with an average of three to four, and the thoracolumbar region a range of zero to four with an average of one. This study also evaluated the number of posterior medullary arteries, which found the cervicothoracic region to have a range of 3–8 arteries with an average of 7 arteries, the midthoracic region a range of 6–14 with an average of 10, and the thoracolumbar region a range of 1–6 with an average of 2–3 (Turnbull et al., 1966). However, the sheer number of arteries cannot be a correlate for the level of perfusion because the arteries of Adamkiewicz feeds the thoracolumbar region, and the numerous vessels that feed the midthoracic region are often minute (Turnbull et al., 1966).

In the sacral region, the segmental artery forms the usual anterior and posterior radicular branches that follow the long nerve roots of the cauda equina upward. None of these sacral branches contributes to the circulation of the anterior or posterior spinal arteries. Besides the usual branches, a small arterial ramus from the sacral spinal artery continues posteriorly through the spinal canal, escaping through the corresponding posterior sacral foramen.

Bergmann and Alexander (1941) discussed the courses of the arteries of the spinal ganglia as observed in specimens from the rhesus monkey and humans. The posterior division of the segmental artery crosses over or under the lateral (distal) part of the spinal ganglion or the common trunk of the spinal nerve and gives off small branches to both divisions of the nerve. It then follows the posterior division of the nerve. The spinal branches arise in front of or behind the ganglion as a common trunk (Bergmann and Alexander, 1941).

In segments in which the anterior spinal branch becomes a significant anterior radicular branch, or medullary artery, the insignificant posterior radicular branch usually arises as its offshoot (Chakravorty, 1971). In segments showing a significant posterior radicular branch, or medullary artery, the insignificant anterior radicular branch usually arises as its offshoot. In such segments that have a significant posterior radicular artery, it has often been observed that the entire dorsal division of the segmental artery took its course below the spinal nerve or the ganglion, before giving off its spinal branches (Bergmann and Alexander, 1941).

The posterior spinal branch divides into two or three small arterial branches, which often communicate with the anterior spinal branch and with each other. They either meet again by gradual approach or form an arcade on the surface of the fibrous capsule of the ganglion. One of the branches continues as the significant posterior radicular branch and pierces the dura. An insignificant radicular branch runs closely with the root; the significant radicular branches, or medullary arteries, enter the dura (Backes and Nijenhuis, 2008).

Having pierced the dura, the significant radicular branches provide small branches for the inner dural

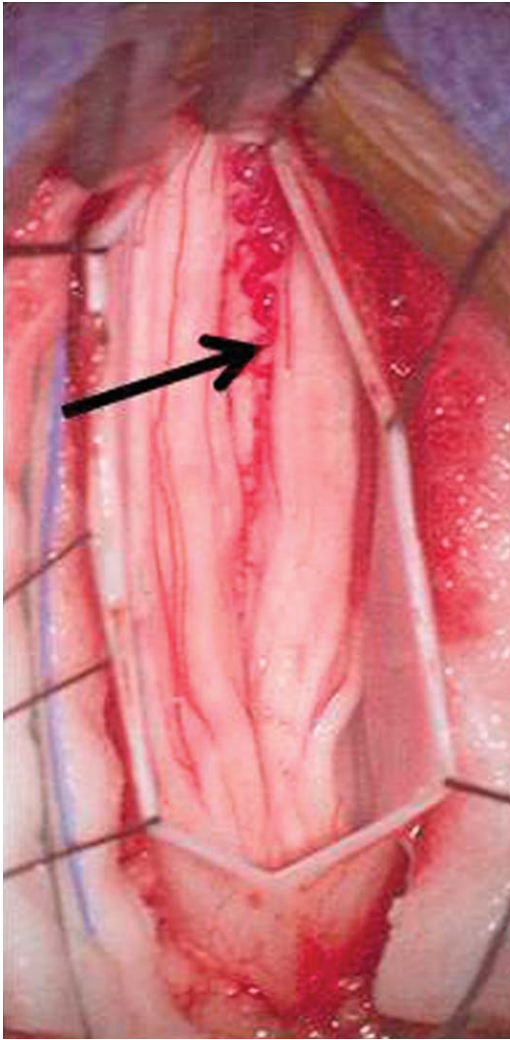


Fig. 7. The so-called conal basket (arrow) seen at operation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

surface and continue toward the cord. After the significant radicular branches enter the dural canal, their caliber is always reduced. The arteries on the surface of the spinal ganglion form a few slender meshes or arcades and furnish two sets of vessels for the ganglion (Biglioli et al., 2004). These offshoots supply the ganglion by piercing its sheath. The arteries enter the ganglion in two groups, one perforating the sheath at the periphery and the other at the poles. These two types of vessels communicate within the ganglion (Lasjaunias and Berenstein, 1990).

The spinal ganglion of the human newborn shows occasional bead-like dilatations of the capillaries and precapillaries, the diameter of which may be about three times the width of the parent vessel. In children who are >3 years of age but still in the first decade of life, these bead-like dilatations are slightly larger, sometimes reaching five times the diameter of the vessel in the course of which they occur. The most

striking bead-like and ampullar dilatations, however, are found in the capillary bed of spinal ganglia of adult human beings from the third decade of life, and they reach 8–20 times the size of the diameter of the vessel in the course of which they occur. These ampullar dilatations occur only in the gray matter, each being about the size of a spinal ganglion cell (Lazorthes et al., 1971; Lasjaunias and Berenstein, 1990).

SPINAL ARTERIES

A single anterior spinal artery traverses along the anterior median sulcus of the cord, and two posterior spinal arteries descend along the posterior aspect of the spinal cord medial to the posterior nerve roots (Fig. 2; Crosby and Gillilian, 1962; Martirosyan et al., 2011). The extraspinal arteries feed into three spinal vessels that run the entire length of the spinal cord (Kadyi, 1889). These three spinal arteries are extrinsic cord arteries and are located along the surface of the spinal cord. The systems of both the anterior and posterior spinal arteries join together at the lower aspect of the conus medullaris to form a complex termed the "conus basket" (Fig. 7; Doppman et al., 1969; Anderson and Willoughby, 1987) with extensions along the filum terminale (Fig. 8). The two terminal branches of the anterior spinal artery pass in a dorsal direction caudal to the fifth anterior sacral roots and anastomose one with each posterior spinal artery, lateral to the fifth posterior sacral roots (Bolton, 1939).

The anterior spinal artery is a longitudinal vessel that runs continuously down the cord in the anterior median sulcus of the cord with variable contributions from radiculomedullary inputs (Biglioli et al., 2004). It stems from branches of the vertebral arteries in the infrabulbar region of the brain just proximal to the basilar artery (Anderson and Willoughby, 1987;

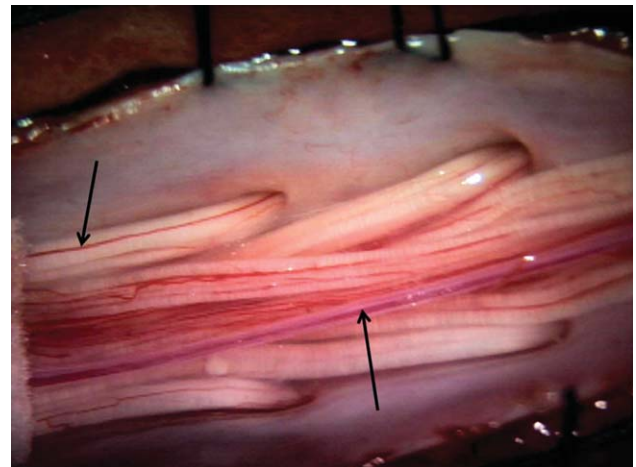


Fig. 8. Intraoperative view of the cauda equina noting radicular arteries (upper arrow) and artery of the filum terminale (lower arrow). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Cheshire et al., 1996; Bowen, 1999). The vertebral arteries unite almost immediately to form a single vessel or remain as paired arteries with free anastomosis as far as the midcervical region of the cord. The paired anterior spinal rami from the intracranial portion of the vertebral artery are variable in size, ~1 mm or less. Absence of one of the pair has been seen a few times, but they are both absent in rare instances according to Spiller (1908). Their union in the majority of individuals occurs intracranially, but the arteries occasionally descend several centimeters before joining (Gillilan, 1958).

The anterior spinal artery is made up of a series of anastomotic networks, rather than a single, uninterrupted tract, and will often bifurcate and vary in size (Infante and Alter, 1970). Although the anterior spinal artery is, for the most part, a single continuous vessel running the entire length of the spinal cord, it cannot be considered an adequate anastomotic channel (Gillilan, 1958).

The diameter of the artery varies greatly from region to region. In the normal individual, there is some correlation between the caliber of the anterior spinal artery and the relative amount of gray matter to be supplied at any level (Gillilan, 1958). The size and, to a lesser degree, the number of medullary arteries as well as the density of the intrinsic vessels, bears a direct relationship to the cross-sectional area of the gray matter of the cord at any given level (Skinhoj, 1954). The large number of cells innervating the extremities and the large number of synapses in the same region necessitate a large blood supply to the enlargements (Gillilan, 1958).

The anterior spinal artery will most frequently bifurcate near the input of radicular feeders, and will give off other branches to supply the cord (Di Chiro, 1971). The anterior spinal artery seems to undulate, looping toward the medullary artery as the latter anastomoses with it (Schossberger, 1974). The medullary artery may bifurcate, sending one limb upward and one limb downward (Shamji et al., 2003). In those rare instances when arteries from both sides join the anterior spinal artery at the same segment, a diamond-shaped pattern may occur, similar to that produced by the anterior spinal rami as they join the vertebral arteries (Gillilan, 1958).

The anterior spinal artery is widest at the point where it meets the artery of Adamkiewicz. The second widest portion is located at the cervical enlargement (Crosby and Gillilan, 1962). Occasionally, it may split into two channels, but almost never below the fifth or sixth cervical vertebrae (Chakravorty, 1971). The anterior spinal artery often becomes narrow in the midthoracic region of the spinal cord, and then widens near the end of the thoracolumbar region where it meets the two posterior spinal arteries at the cruciate anastomosis (Crosby and Gillilan, 1962). Two or perhaps three medullary arteries join the anterior spinal artery in the upper thoracic region. When another artery is present, it is usually small and located between the fifth and seventh thoracic segments. Another lumbar medullary artery, in addition to the artery of Adamkiewicz, occasionally joins the anterior spinal artery. It is small and may enter from either

side a few segments below the artery of Adamkiewicz (Gillilan, 1958).

These paired longitudinal vessels start from the region of the vertebral arteries proximal to the posterior inferior cerebellar artery (PICA), or at the PICA itself, and run more or less discontinuously along posterolateral cord, with sporadic contributions from radiculopial inputs. The posterior spinal arteries are parallel vessels that run along the posterior aspect of the spine and originate from branches of the vertebral arteries (Herren and Alexander, 1939). These arteries are in fact two posterior plexiform channels (Cheshire et al., 1996). Like the anterior spinal artery, the upper ends of these vessels originate as branches from the intracranial portion of the vertebral artery (Suh and Alexander, 1939). They swing lateralward around the brain stem and then caudalward along the posterolateral surface of the cervical cord. They are distinct single vessels only at their origin from the vertebral arteries (Uotani, 2008). Thereafter, they become irregular anastomosing channels, retaining to a large degree their embryonic plexiform pattern (Gillilan, 1958). In the cervical region, there may be two pairs of longitudinal vessels posteriorly, including lateral spinal vessels ventral to the dorsal root and a posterior spinal vessel dorsal to that same dorsal root (Siclari et al., 2007).

Of these two longitudinal vessels, the lateral spinal vessel was first described in the literature by Cruveilhier in 1867 and later named by Lang in his (1981) account of several dissections of a spinal artery he named the "lateral spinal artery." The artery originates lateral to the medulla from either the intradural vertebral artery or the PICA. It courses parallel to the spinal component of the 11th cranial nerve, heading in a caudal direction. On its course it travels anterior to the posterior spinal roots to C-4 and posterior to the dentate ligament. Along its path, the lateral spinal artery anastomosis with branches of PICA at the level of the restiform body, with extradural arteries originating from the occipital or vertebral arteries at each metameric level, and with the contralateral system posteriorly (Lasjaunias et al., 1985). The lateral spinal artery terminates dorsal to the posterior root of the spinal nerve C-4 or C-5 with the posterior spinal vessel into a single pair of posterior longitudinal vessels (Siclari et al., 2007).

These arteries are not uniform throughout their length and may be seen as distinct only at their origins near the cranial portions of the vertebral arteries. Like the anterior spinal artery, the posterior spinal arteries are widest in the cervical and lumbar regions and narrowest in the thoracic region (Crosby and Gillilan, 1962). In the thoracic region, the posterior spinal arteries may become so narrow that they seem to terminate (Turnbull et al., 1966). These vessels travel the entire length of the cord, sending off vessels to the posterior plexiform channels near the entrances of the rootlets of the posterior nerves, and occasionally being supplied by radicular feeders, until they anastomose with the anterior spinal artery near the terminal conus medullaris (Spiller, 1908).

The posterior spinal channels are joined at intervals by posterior medullary arteries, averaging six to eight

on a side, which are much smaller than the anterior medullary arteries. Although posterior and anterior medullary arteries may contribute to their respective spinal arteries at the same segmental level, this is usually not the case. In most individuals, there are two posterior medullary arteries of slightly more prominence than others in the series, which join the posterior spinal arteries in the vicinity of the lumbar enlargement. The last large artery can be considered the great posterior medullary artery, but it is never so large or so important as its anterior counterpart, the artery of Adamkiewicz (Gillilan, 1958).

INTRAMEDULLARY ARTERIES

The intramedullary arteries represent the terminal point of the spinal arterial system before the spinal capillaries (Turnbull et al., 1966). The intramedullary arteries are also termed the intrinsic cord arteries (Lasjaunias and Berenstein, 1990). These arteries supply the nerve tissue of the spinal cord and come from the anterior spinal artery, the two posterior plexiform channels formed by the posterior spinal arteries, and the fine network interconnecting them (Gillilan, 1958). This intrinsic portion of the arterial supply to the spinal cord is made up of two systems: the centrifugal system of arteries consisting of 250–300 central, or sulcal, arteries and their branches; and the centripetal system of arteries consisting of the pial plexus and its branches (Fig. 2; Crosby and Gillilan, 1962). Intrinsic anastomoses consisting of axial and longitudinal precapillary connections interconnect the intrinsic cord arteries in all planes from one to another at the same axial level and to vessels cranial and caudal to that level (Lasjaunias and Berenstein, 1990).

The vascularity of the gray matter is greater than that of the white matter (Herren and Alexander, 1939). The lamellae and strands of white substance within the spinal ganglia and both roots contain relatively few capillaries, the loops of their loose and wide-meshed capillary bed being long and generally parallel with the course of the fibers. In the gray matter of the spinal ganglion, abundant and dense capillary networks are observed. Their meshes are released from fairly short precapillary arterioles and show a frequently and irregularly curved, or even tortuous, course. Almost every individual ganglion cell is surrounded by its own loop or loops (Bergmann and Alexander, 1941). Craigie (1931), in a study of the brain and spinal cord of the albino rat, reported that the poorest part of the gray matter was 1.5 times more vascular than the richest white matter (Gillilan, 1958). Dunning and Wolff (1937) found that the vascularity of the parietal gray matter was 2.33 times greater than that of the parietal white matter. Thus, white matter seems to have a low metabolic rate compared with gray matter (Gillilan, 1958).

The pial plexus is the most superficial component of this spinal arterial network, and is known as the peripheral arteries or vasocorona (Fig. 2; Di Chiro, 1971). Specifically, the penetrating branches of this vascular plexus, which enter the spinal cord at right

angles, constitute the centripetal system of arteries (Di Chiro et al., 1970). The radial perforating arteries arise from the pial network, penetrate the cord deeply, and primarily feed white matter tracts (Lasjaunias and Berenstein, 1990). Arterial branches from this peripheral plexus enter the white matter at right angles. Some of these branches break up immediately into the loose rectangular network characteristic of the white matter and supply from one-third to one-half of the outer rim of the spinal cord. Other penetrating branches are seen to cross the white columns and anastomose directly with the capillary nets within the anterior gray columns. The rectangular meshes of the capillaries in the white matter are oriented in the direction of the nerve bundles. In the region of the anterior white commissure, the capillaries take a transverse course, parallel to the crossing axis cylinders (Gillilan, 1958).

Between the two posterior spinal arteries, there are many small anastomosing arterioles, and together they form the posterior pial plexus (Crosby and Gillilan, 1962). The posterior plexus is, in fact, a continuation of the lateral and anterior pial plexuses formed by arteriolar branches from the anterior spinal artery, with a tendency for the formation of heavier longitudinal channels located near the entering posterior nerve roots (Crosby and Gillilan, 1962).

The posterior, anterior, and lateral parts of the pial plexus are thus composed of circumferential vessels that bridge the anterior and posterior spinal arteries and that may emanate from the radicular branches (Chung, 1926; Anderson and Willoughby, 1987; Edwards and Halbach, 1993). These peripheral or pial vessels run in a relatively transverse fashion along the perimeter of the spinal cord and will either terminate into the pia mater, or penetrate the cord itself to supply adjacent white matter, the tips of the posterior horns, the majority of Gall and Burdach's tracts, and the lateral aspects of the anterolateral tracts (Hughes and Brownell, 1964; Lasjaunias and Berenstein, 1990; Lo et al., 2002). This variable network of longitudinal and interconnecting axial vessels has anastomoses primarily to the posterior spinal arteries with only very small connections to the anterior spinal artery (Tveten, 1976; Prestigiacomo et al., 2003).

The posterior third of the spinal cord is the site of a vascular lesion less frequently than the anterior two-thirds. The reason for this is not clear, but perhaps it may be because of the plexiform character of all arteries on the posterior surface and a greater number of medullary arteries. When there is involvement of the pial plexus, as in generalized luetic meningitis, only the outer rim of white matter, which is the region supplied by the penetrating arteries from the pial plexus, is affected. The anastomosis between the pial plexus and the central branches of the anterior spinal artery provides only a potential collateral circulation to the anterior two-thirds of the spinal cord and is subject to great individual variation. Following an acute arterial occlusion, the superficial arterial anastomoses and the capillary plexuses are functionally insufficient to prevent damage to the tissues of the spinal cord at the segments where the interruption occurred (Gillilan, 1958).

The other half of the intramedullary network consists of the central, or sulcal, arteries (Crosby and Gillilan, 1962). This component stems from the anterior spinal artery at right angles; in the anterior median fissure, it penetrates the anterior white commissure, where it diverges both transversely, left and right, and longitudinally to enter the gray matter of the cord (Zarins et al., 1983; Schalow, 1990). The density of these arteries is thought to correspond to the metabolic demand of the underlying gray matter; consequently, they are particularly numerous throughout the cervical and lumbar enlargements compared with the mid-thoracic segments (Sahs, 1942; Shamji et al., 2003).

The intrinsic vasculature is organized differently for the anterior gray matter and the posterior gray matter. The bulk of the anterior gray matter is not uniform, but is arranged as a string of beads, each bead comprising a segmental nuclear mass. This beaded arrangement of the anterior gray matter does not hold true for the posterior gray column. Here, the arrangement is one of a solid column, varying somewhat in thickness at different levels (Siclari et al., 2007). The arrangement of the intrinsic vasculature for these two areas reflects their respective structures. There is a constant depth of vascular bed in the posterior gray column and a series of bulbous arborizations within the nuclear beads in the anterior gray column (Herren and Alexander, 1939).

Longitudinal branches of the central arteries have a high degree of overlap, but it is debated whether or not they anastomose at locations other than the capillary level (Jellinger, 1972). The central arteries are responsible for the perfusion of the anterior horns, the commissure, the base of the posterior horns, and the anterolateral white matter (Gillilan, 1958); in total, these arteries supply approximately the anterior two-thirds of the spinal cord (Hughes and Brownell, 1964). More specifically, they also perfuse Clarke's columns, the pyramidal tracts, the spinothalamic tracts, the anterior white columns, and the anterior aspect of Goll and Burdach's tracts (Gillilan, 1958; Bowen, 1999). For all levels of the cord, each central artery contributes to the arterial supply of only one side of the spinal cord, either the right or the left (Crosby and Gillilan, 1962).

The central arteries leave the anterior spinal artery singly, not in pairs, and, in the depths of the anterior median fissure, turn alternately to the right and to the left. Kadyi (1889) was the first to describe the central arteries as unbranched vessels turning alternately to the right and to the left.

The capillaries of the anterior horn area anastomose with similar networks from the central arteries immediately above and below. Where the central arteries are numerous, as in the lumbosacral enlargement, they are more nearly horizontal, and the segment supplied is short. In the thoracic region, the number of central arteries is reduced; therefore, their course tends to be oblique or even longitudinal. The capillary networks here are spread over a long segment. The vessels in the cervical cord are intermediate in plane and in territory supplied (Gillilan, 1958).

Thus, the central arteries have different organizations in the lumbosacral, cervical, and thoracic portions of the spinal cord. In the lumbosacral region, the central arteries leave the anterior spinal artery at right angles and pass upward in the septum. Only in the lumbosacral region, and here only occasionally, is a central artery seen to divide into two central branches from a short common trunk, and these occasional branches have not been observed to supply more than the same side of the spinal cord. In addition, the central arteries for either side are not regularly alternating (Crosby and Gillilan, 1962).

In the cervical region, the central arteries leave the anterior spinal artery in a slightly oblique course. This region demonstrates the greatest regularity in vessels supplying the alternate sides of the cord. Herren and Alexander (1939) reported that there rather constantly appeared to be two arteries on each side, and thus four central arteries altogether, for each segment. The distribution of these vessels is like that in the lumbar region.

In the thoracic region, the central arteries leave the anterior spinal artery with considerable obliquity and run dorsally and cranially in the septum. There is considerable irregularity in the alternate supply to either side, and occasional areas are seen where one central artery alone supplies one side for a whole segment. Herren and Alexander (1939) observed a substantial number of descending and ascending intraspinal arterial branches that compensate for the thoracic region's relatively poor blood supply. The intraspinal distribution of the central artery is similar in every other way to that in the lumbar and cervical regions (Kadyi, 1889).

The number of central arteries supplying each cord segment varies with the region of the cord. They are most numerous in the lumbosacral enlargement, and least numerous in the thoracic region. Finally, the central arteries have a bilateral embryologic origin; during development, they stemmed from the paired anterior spinal channels, which later fuse into a single median channel. The central arteries, however, do not fuse, but keep their lateral relationship. This origin is reflected in the termination of the central arteries in the commissure itself and the subsequent scant communication between the two halves of the spinal cord (Jellinger, 1972).

In summary, the capillary network formed by the central arteries surrounds the cells of the anterior horns, the intermediate and commissural cells, and a variable part of the base of the posterior horn. The lateral and anterior white columns are served by penetrating vessels from the pial plexus. Some of the penetrating vessels anastomose with the capillary plexus in the anterior horns. The posterior third of the spinal cord is supplied by penetrating arteries from the pial plexus, with which 10 to 20 posterior medullary arteries anastomose. Thus, there are two levels of anastomosis of the arteries to the spinal cord: a superficial anastomosis in the pial plexus, and a capillary anastomosis found mostly within the gray matter (Kadyi, 1889; Jellinger, 1972).

Becske and Nelson (2009) noted that the anatomic distribution of the spinal arteries establishes three

watershed zones. The first is along the longitudinal axis of the upper thoracic spinal cord between the arteries of the cervical and lumbar enlargements. The second is over the anterolateral surface of the cord between circumferential pial branches of the anterior spinal artery and the posterior spinal arterial arcade. The third is along the gray/white junction between the intramedullary territories of the central arteries and the peripheral arteries. There is overlap between the peripheral and central arteries, which produces a watershed zone, but the exact location is debated by a small number of angiographic studies (Tator and Koyanagi, 1997). Although a watershed zone exists between these two systems, only a minuscule amount of nonfunctioning capillary anastomoses exists between them, and they are considered terminal systems (Thron, 1988).

HEMODYNAMICS

Hemodynamics of the arterial supply of the spinal cord is an important factor to consider in the study of vascular pathology and imaging modalities. The direction of blood flow through the spinal arterial network plays a crucial role in the maintenance of tissue perfusion and the prevention of ischemic pathology. Di Chiro et al. (1970) used angiography to demonstrate that both ascending and descending flow exists in the anterior and posterior spinal arterial pathways, and that further watershed zones are created where opposing currents meet (Di Chiro, 1971).

Bolton (1939) studied the direction of blood flow in the anterior and posterior spinal arteries. The usual direction of blood flow in the anterior spinal artery was from above downwards. The caliber of the anterior spinal artery at different levels of the spinal cord varied considerably. It appeared to be of very small dimensions immediately above the entry of a spinal artery, thus forming a mechanical barrier to the upward flow of blood. These experiments showed that down to the level of the lower cervical or upper thoracic segments the flow was from above downwards, and derived mainly from the vertebral artery or from the PICA. At lower levels of the cord, however, the direction of flow seemed to be in the opposite direction.

On the posterior surface of the spinal cord, narrowing of the vessels as seen on the anterior surface was not observed, and the blood from the vertebral arteries reached the level of the highest thoracic segments in an uninterrupted flow (Edwards and Halbach, 1993). At this point, the vertebral flow appeared to cease, and the blood below this level was derived from the caudal part of the anterior spinal artery (El-Toraei and Juler, 1979).

Usually, blood will flow in opposite directions from the bifurcation of each subsequent segmental medullary artery, with the exception of the artery of Adamkiewicz, which has a predominantly downward flow (Di Chiro et al., 1970; Di Chiro, 1971). Blood flow from two adjacent radicular tributaries takes place in the anterior and posterior spinal arteries in opposite (converging) directions. Recent studies confirmed that

bidirectional and reversible currents of blood flow exist in the longitudinal arteries, indicating the existence of external watershed zones (Jellinger, 1972).

Watershed zones are an important concept to note. In the presence of stenosis or obstruction of large extraspinal arterial channels, the collateral circulation provided by the anastomoses of the afferent arterial pathways is inadequate since both the longitudinal and the perimedullary arterial systems are insufficient, and the intramedullary anastomoses that exist only through the capillaries are without functional value. Critical areas of vascular supply, referred to as "watershed zones," are located at the periphery of a territory supplied by a particular artery and its overlap with an adjacent territory of supply. These areas, which represent preferential sites of disorders of microcirculation with diminished blood flow, are variably located in the upper thoracic segments and within the cord where the central and peripheral systems overlap. Under certain pathological conditions, there may be selective damage of the spinal gray matter, the particular vulnerability of which is due to its great density of capillaries (Hughes and Brownell, 1964).

However, the converging currents of the anterior and posterior spinal arteries allow for ample collateral flow in the event of arterial occlusion (Hughes and Brownell, 1964; Infante and Alter, 1970). This protective mechanism is not merely beneficial to spinal cord blood flow, but rather for the entire cardiovascular system (Doppman et al., 1969; Di Chiro et al., 1970; Di Chiro, 1971). In fact, the ascending current from the cervical radicular feeder (usually C3) can provide retrograde flow to the basilar artery in the event of an obstruction of one or both of the vertebral arteries (Edwards and Halbach, 1993). Throughout the cardiovascular system, adaptations in collateral flow can occur in response to physiologic or pathologic need (Hughes and Brownell, 1964). This mechanism, referred to as the steal phenomenon, will cause the dilation of spinal arteries to serve as collateral flow in the event of congenital arteriovenous malformations, atherosclerosis, angiomas, etc. (Infante and Alter, 1970).

Reversal of blood flow currents in the anterior and posterior spinal arteries may occur in pathological conditions due to hemodynamically active lesions (e.g., arteriovenous malformations in and outside the cord) or due to stenotic or obstructive vascular disease located either in the spinal cord arteries or in the major extraspinal tributaries. Reversals of blood flow direction in the spinal cord arteries may cause steal phenomena with resulting degrees of cord ischemia (Jellinger, 1972).

Comparative measurements of the blood flow of both the brain and spinal cord in dwarf pigs using heat-clearance probes demonstrated that under physiological and pathological conditions the spinal and cerebral circulations react in similar ways. The influence of vaso-active substances on the cerebral and spinal circulations was tested under physiological conditions. Most of these substances caused only brief changes in the circulation or had no effect whatsoever. The same was true for anesthetics. Only papaverine

and its derivatives caused a considerable increase in both cerebral and spinal cord circulations. Euphylline constantly caused a reduced blood flow in the central nervous system. These data suggest that the reactions of the spinal cord and brain vasculatures to vaso-active substances are very similar. Under physiological conditions, compensation for circulatory alterations caused by vasoactive drugs, except for papaverine and its derivatives, is rapidly achieved by autoregulatory mechanisms, which apparently are the same in the brain and spinal cord. Under pathological conditions (e.g., experimental cord edema or spinal cord compression), the autoregulation of spinal cord hemodynamics is disturbed or even abolished. The blood flow then depends mainly on the systemic circulation rate, the blood pressure, and changes in tissue pressure (Tator and Koyanagi, 1997).

Under physiological conditions, the regulation of spinal cord hemodynamics is similar to that of the brain. Under normal conditions, rise in the arterial $p\text{CO}_2$ causes a transient increase in spinal blood flow, which, under pathologic conditions (e.g., in spinal tumors), is not observed. Application of vasoconstricting substances causes transient increase of spinal cord circulation due to an increase in systemic blood pressure, which, however, will be nullified within 1 min by spinal autoregulation. Removal of intramedullary and extramedullary tumors results in rapid focal increase of spinal cord circulation. Increased $p\text{CO}_2$ has little or no effect on spinal cord flow in the setting of such tumors, but it causes rapid increase of spinal cord circulation after removal of the pathological process. In cases of intramedullary tumor, increased $p\text{CO}_2$ causes a rapid reduction of spinal circulation due to a "steal syndrome," whereas application of euphylline induces a "counter steal effect" with increased cord flow. Additional apnea probably increases intrathoracic pressure and also impairs drainage in the large epidural venous plexuses, thereby resulting in a reduction of the difference in arteriovenous pressure within the spinal cord. As a result, the venous portion of the vascular system is hemodynamically of greater significance for the spinal cord flow than for the cerebral circulation. Thus, under certain pathological conditions, the application of vasodilating substances may be dangerous because they may cause steal phenomena with resulting ischemia of the spinal cord (Jellinger, 1972).

From these experimental data, it can be concluded that any therapeutic attempt to improve spinal cord circulation using vasoactive drugs will be of little value. Such improvement may be achieved only by influencing the total circulation and by rapid removal of compressive edema of the spinal cord or any other pathological condition.

The arteriovenous circulation time is an important factor in the differentiation between arteries and veins, as will be discussed shortly. This parameter has been determined by timing the appearance of the spinal vein with serial catheter angiography in healthy subjects, and is 9–10 sec in the cervical cord and ~12 sec in the lumbar cord. However, multiple factors may affect the circulation time, including the hemodynamic situation of the patient and the influence of anesthesia

(Backes and Nijenhuis, 2008). Contrast agent arrival times are determined in the aorta (e.g., at the cranio-caudal region of the artery of Adamkiewicz), which may provide arrival times somewhat deviant from the actual arrival times in intradural arteries, particularly in patients with many occluded segmental arteries (Backes and Nijenhuis, 2008).

The arterial supply of the spinal ganglia has been described as being generally inefficient. This inefficiency is exemplified by the fact that most of its arterial vessels do not enter the ganglion in the main direction of the blood stream, but branch off at right angles or recurve against the main direction of blood flow (Becske and Nelson, 2009).

This review emphasizes the hemodynamics of arterial blood flow to the spinal cord and the pathology associated with disturbances in the arterial supply. However, in addition to arterial disorders, disturbances of the venous drainage are important to note. The low pressures that produce circulatory disturbances speak in favor of the view that in the setting of slowly progressing compressive lesions, an impairment of the venous drainage is primarily responsible for the deficient circulation. In a considerable proportion of spinal cord lesions, the pattern suggests an impairment of the venous drainage (Levy and Strauss, 1942; MacNalty and Horsley, 1909; Na et al., 2007).

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